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Experimental Verification of Corrosive Vapor Deposition Rate Theory in High Velocity Burner Rigs

(NASA-TM-87287) EXPERIMENTAL VERIFICATION
OF CORROSIVE VAPOR DEPOSITION RATE THEORY IN
HIGH VELOCITY BURNER RIGS (NASA) 12 p
HC A02/MF A01 CSCL 20D

N86-22890

Unclas
G3/34 05880

Süleyman A. Gökoglu and Gilbert J. Santoro
*Lewis Research Center
Cleveland, Ohio*

Prepared for the
3rd Conference on High Temperature Alloys for Gas Turbines
and Other Applications
sponsored by the Commission of the European Communities
Liège, Belgium, October 6-9, 1986

NASA



EXPERIMENTAL VERIFICATION OF CORROSIVE VAPOR DEPOSITION RATE THEORY IN HIGH VELOCITY BURNER RIGS

Süleyman A. Gökoğlu* and Gilbert J. Santoro
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135 U.S.A.

E-2993

ABSTRACT. The ability to predict deposition rates is required to facilitate modelling of high temperature corrosion by fused salt condensates in turbine engines. A corrosive salt vapor deposition theory based on multicomponent chemically frozen boundary layers (CFBL) has been successfully verified by high velocity burner rig experiments. The experiments involved internally air-impingement cooled, both rotating full and stationary segmented cylindrical collectors located in the crossflow of sodium-seeded combustion gases. Excellent agreement is found between the CFBL theory and the experimental measurements for both the absolute amounts of Na_2SO_4 deposition rates and the behavior of deposition rate with respect to collector temperature, mass flowrate (velocity) and Na concentration.

1. INTRODUCTION

Trace amounts of impurities in hot gas flow systems can lead to the deposition of corrosive salts (i.e. sodium sulfate) on cold surfaces, severely deteriorating system performance. The objective of the "hot" corrosion research at NASA Lewis Research Center is to predict hot section component life, specifically for combustion turbine engine applications. For this purpose less expensive (cf. full scale engine testing) high velocity - high temperature (and high pressure) burner rigs, nominally operating at Mach 0.3, were built to measure deposition rates of sodium sulfate on inert, internally cooled, cylindrical collectors located in the cross stream of Na-salt-doped combustion gases. The purpose of internal cooling (by air impingement) was to independently control the collector surface temperature irrespective of combustion gas and prevailing dew point temperatures. The details and results of the previous work were reported in Refs. 1 and 2.

*Case Western Reserve University, Dept. of Mechanical and Aerospace Engineering, Cleveland, Ohio 44106 and NASA Resident Research Associate.

The corrosive deposits are formed primarily by the vapor transport of precursors (e.g. NaOH, Na, Na_2SO_4 , etc. in the case of Na_2SO_4 deposition) across the boundary layer. A comprehensive, chemically frozen boundary layer (CFBL) vapor transport theory has been formulated to predict deposition rates [3,4]. However, the presence of salt solution droplets capable of inertially impacting on the collector surface and the complicated aerodynamic conditions prevailing in the burner rig deposition test configuration precluded the intended comparison of theory and experiment. Both analytical and experimental modifications were necessitated to gain predictive capabilities.

The procedure to eliminate the droplets from the system, the analytical method developed to handle aerodynamic complexities as well as the experiments performed to provide the theory with the required parameters were discussed in detail in Refs. 5 and 6, and are briefly summarized here. In addition, a new approach adopted to facilitate heat/mass transfer rate predictions using a simple collector geometry is explained. This approach involves segmented collectors which are 20° on both sides of the forward stagnation point of the previous cylindrical collectors, simulating the nose region of blades.

The excellent agreement between the predictions and the experimental measurements of Na_2SO_4 deposition rates verifies the CFBL theory and its expected flowrate (Reynolds number) and contaminant concentration dependencies.

2. BACKGROUND

Previously, Na_2SO_4 deposition rates predicted by the CFBL theory and observed experimentally had two regions of disagreement [1,2]. The lower experimental deposition rate measurements for collector temperatures above the melting point of Na_2SO_4 were theoretically and experimentally explained by the shear-driven molten deposit layer run-off from the smooth collector surface [1,2,7]. The higher experimental values for collector temperatures below the melting point of Na_2SO_4 , however, were caused by the original procedure of air atomization of the various aqueous sodium salt solutions into the combustor (Fig. 1). The atomized salt solution droplets did not have sufficient residence times in the combustor to completely vaporize. This resulted in large enough droplets capable of inertially impacting on the collector surface. This claim was supported by vaporization time calculations based on experimentally determined droplet size distribution and deposition rate calculations based on the inertial impaction theory. It was further verified by the particle capture experiments where a platinum foil attached to a water cooled support was exposed to the combustion gases for a few seconds [2]. To insure that the sodium species were entirely in the vapor phase in the combustor, a new procedure was adopted which involved physically mixing a solution of sodium acetate in ethanol with Jet A-1 fuel in the fuel nozzle cavity and spraying this mixture through the fuel nozzle into the combustor. Because the residence time was increased due to a longer distance to be traveled to exit the combustor and because the fuel/alcohol mixture burns faster (cf. water solution

droplets vaporize), the droplets were eliminated. This was also verified by the absence of particles in particle capture experiments.

The second major problem encountered in the past originated from the dimensional restraints of the experimental setup. The jet throat diameter of 2.54 cm dictated by a practical combustor size and the collector diameter of 1.90 cm dictated by its internal impingement cooling feature resulted in aerodynamics that was analytically very difficult to treat (Fig. 2). The facilitated ambient air entrainment and penetration into the hot gases around the collector cause significant cooling of the mainstream and dilution of the precursor contaminants. Therefore, the burner rig setup is not an ideal cylinder in crossflow situation where the collector would be completely immersed in an isothermal stream with a contaminant concentration equal to that in the burner exit nozzle and for which conventional heat/mass transfer rate prediction methods are readily available. To remedy this problem two parallel approaches were taken.

In the first approach, two series of experiments were conducted to provide necessary data to analytically treat the aerodynamic complexity of the relative jet stream-collector geometry. The first series of experiments was performed to determine the angular variation of the mass transfer coefficient around the collector utilizing the naphthalene sublimation technique. The second series of experiments was performed to determine the angular variation of temperature and contaminant concentration utilizing a procedure of measuring angular steady state collector temperature distribution in the flame. These two sets of experiments provided sufficient mass transfer coefficient and cooling/dilution effect information to devise an analytical procedure to predict deposition rates using the CFBL theory. The success of this approach is demonstrated in Fig. 3 where the bars represent experimental scatter. Because some Na salt deposition occurs on the inner wall of the burner liner after fuel and alcohol burn away, the amount of Na fed into the system has to be corrected for that loss to obtain the actual Na concentration in the burner exit combustion gases. The amount lost (~25 percent) was determined by chemically analyzing the amount that deposited on the liner wall for known amounts fed into the combustor. The experimental scatter in this determination is reflected by the uncertainty (shaded) region of the theoretical curve. The meticulous description of both the analytical and experimental procedure given in Refs. 5 and 6 will not be repeated here.

In the second approach only a segment which is 20° on both sides of the forward stagnation point of the previous cylindrical targets is used as the collection (deposition) surface (Fig. 4) and will be discussed below. The advantage of using a segmented collector was to eliminate the mainstream cooling and dilution effect due to the entrainment of ambient air, thereby simplifying the analytical treatment of the problem because the combustion gas jet directly impinged on the collector surface.

3. SEGMENTED COLLECTOR DEPOSITION EXPERIMENTS

The schematic of the present burner rig setup and the typical test parameters are shown in Fig. 5 with the new contaminant feed method and the segmented collector. The above-mentioned naphthalene sublimation technique has been further exploited to determine the heat/mass transfer coefficient of the stagnation point region. The same experimental method also provided the information on the effect of mainstream turbulence on enhancing the heat/mass transfer rates to burner rig targets [5,6].

The advantage of eliminating the ambient air entrainment problem by using segmented collectors should, however, be compared with larger deposition surfaces available in the case of full cylindrical collectors. Given the practical run time limitations, constraints on the solubility of Na-acetate in alcohol or alcohol solution pump feed rate and the precision of the method of determination of the amount of deposit on the collector (weighing and/or chemical analysis), one can not select the segmented collector approach as superior to the full collector approach.

The excellent agreement between the predictions of the CFBL theory and the experimental measurements for Na_2SO_4 deposition rates on the plateau region (where the collector temperature is sufficiently lower than the prevailing dew point temperature) is depicted in Fig. 6. Because of the molten deposit layer run-off due to aerodynamic shear, no experiments were conducted for collector temperatures above the melting point of Na_2SO_4 . Typical test conditions were $\text{Ma} = 0.3$, $\text{Re} = 1.83 \times 10^4$, $T_0 = 1673 \text{ K}$ and Na concentration of about 5 ppm by weight with respect to the combustion air. The bars indicate experimental scatter and the shaded area is the CFBL prediction with a ± 5 percent uncertainty in the burner exit Na concentration due to losses in the burner liner.

A more complete verification of the CFBL theory is shown in Fig. 7 for the plateau region deposition rates using segmented collectors. The theory predicts that the Na_2SO_4 deposition rate is directly proportional to the Na concentration in the combustion gas and to the square root of the Reynolds number. Five sets of experiments were done where both the Na concentration and the Reynolds number (mass flowrate and Mach number) were changed simultaneously. The scatter in the experimental data and the uncertainty in the Na concentration is shown by the error bars and by the shaded theoretical prediction band. When $\dot{m}/\text{Re}^{1/2}$ is plotted against ω_∞ , the fact that the curve passes through the origin and is linear verifies that, indeed, the CFBL theory correctly predicts the Re and ω_∞ dependencies of the deposition rate.

4. CONCLUSIONS AND IMPLICATIONS

The chemically frozen boundary layer multicomponent vapor deposition theory has been successfully verified by high velocity burner rig experiments. The experiments involved internally air impingement cooled both rotating full and stationary segmented cylindrical

collectors located in the crossflow of sodium-seeded combustion gases. Excellent agreement is found between the CFBL theory and the experimental measurements for both the absolute amounts of Na_2SO_4 deposition rates and the behavior of deposition rate with respect to collector temperature, mass flowrate (velocity) and Na concentration.

This predictive capability is a very significant step in understanding the relationship between the deposition and hot corrosion rate toward an ultimate goal of turbine engine hot section component life prediction. In the light of the cost of actual turbine engine tests, it is essential to establish simulation criteria providing the ability to interpret laboratory experiments and to extrapolate information to turbine engine operation conditions. However, not even a standard testing procedure exists for determining the hot corrosion resistance of materials or for studying the mechanism of attack, as discussed more thoroughly in Ref. 8. Meaningful tests and comparisons are possible only if "equivalent" conditions are reproduced via some established criteria, interrelating closely-linked phenomena. Among the multitude of choices available for such criteria one can list the convective flux of the gas-phase contaminant, the salt-contaminant dew point and deposition rate, the thicknesses of the corrodant liquid deposit layer and the protective oxide layer on the immersed surface, the rate of dissolution of the oxide coating and the alloy composition. Immediate knowledge of the effect of changing aerothermal conditions of a corrosion test on deposition rate is, thus, a valuable milestone toward the determination of these vital parameters. References 9 and 10 are examples of such initial studies where attempts were made to couple the interaction between deposition and hot corrosion rates based on more fundamental principles.

NOMENCLATURE

d cylindrical collector diameter

F/A fuel to air mass flow rate ratio

\dot{m} deposition rate of sodium sulfate

Ma_∞ Mach number, $U_\infty / U_{\text{sonic}}$

Re Reynolds number, $(\rho_\infty U_\infty d) / \mu_\infty$

SMD Sauter mean diameter (diameter of a monodispersoid with the same surface area as the droplet size distribution)

T_0 stagnation temperature of combustion gases

U_∞ combustion gas velocity at nozzle exit

μ_∞ combustion gas viscosity at nozzle exit

ρ_{∞} combustion gas density at nozzle exit

ω_{∞} sodium mass fraction in the combustion gases

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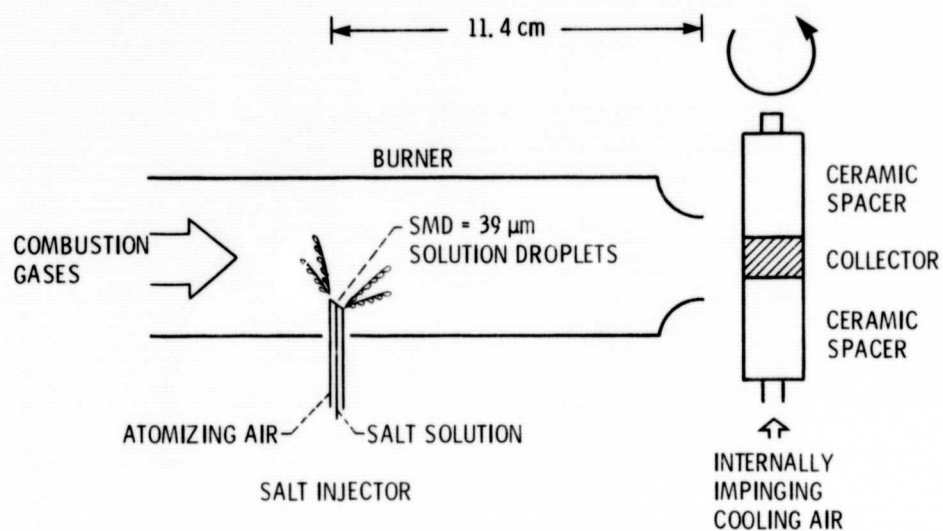


Figure 1. - Burner rig and collector configuration with air atomizing aqueous salt solution injector. The Sauter mean diameter, SMD, of the solution droplets was determined by a Malvern laser droplet size analyzer.

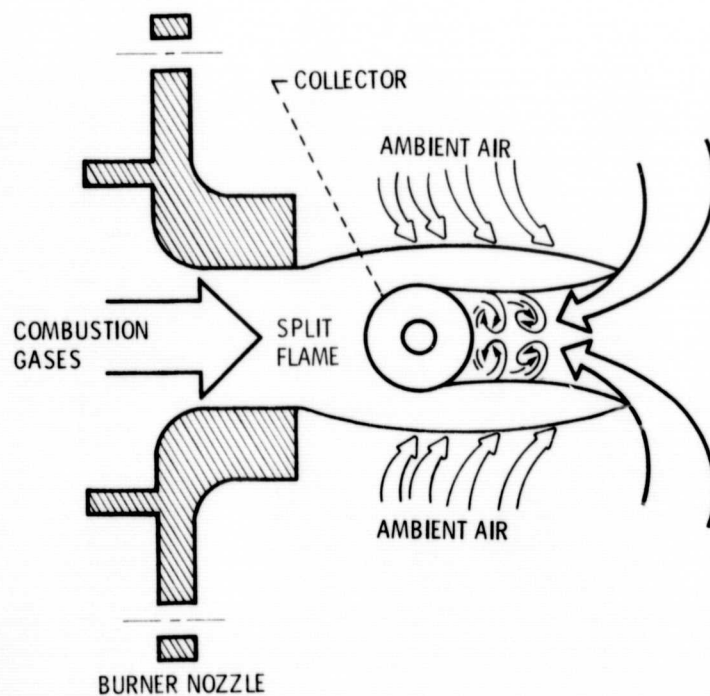


Figure 2. - Top view schematic of the burner exit nozzle and collector configuration illustrating ambient air entrainment.

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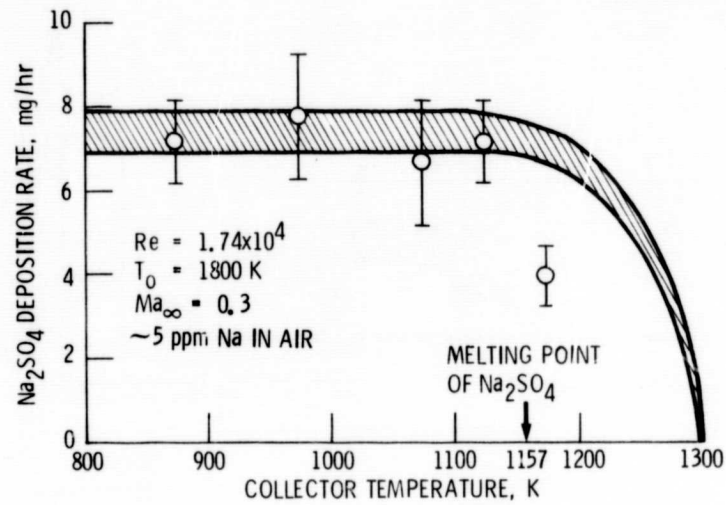


Figure 3. - Comparison of predicted and experimental sodium sulfate vapor deposition rates on full cylindrical collectors. Complete dopant vaporization was assured by mixing and burning sodium acetate/ethanol solution with the Jet A-1 fuel.

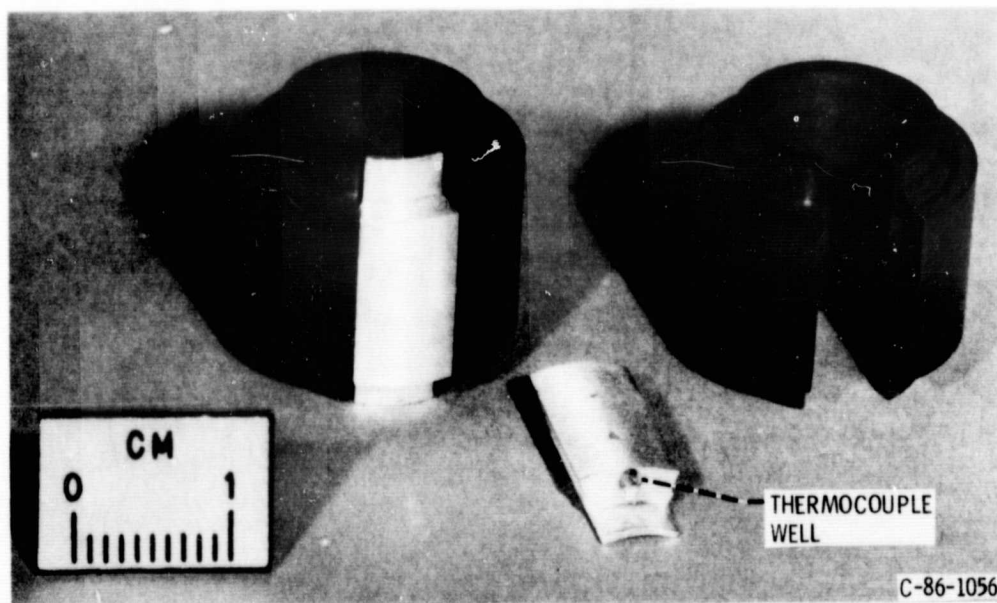


Figure 4. - The segmented collector assembly consisting of a Pt - 20 Rh segment, with a thermocouple well, which snugly slips.

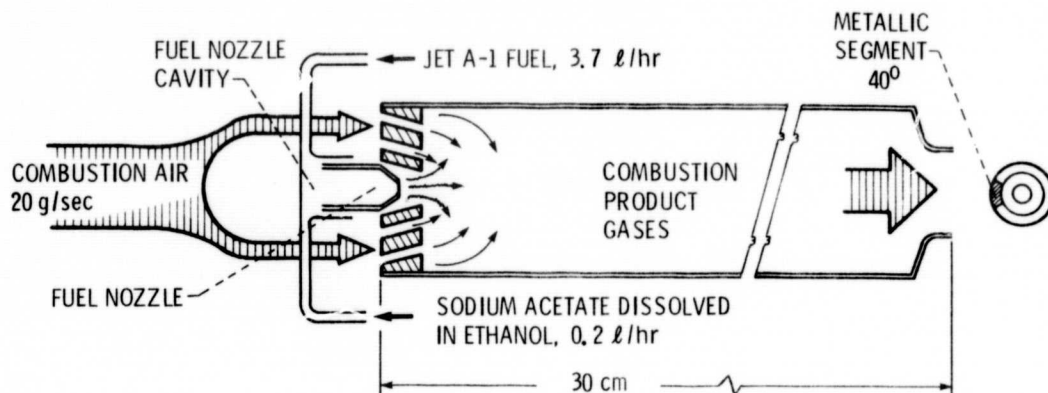


Figure 5. - Burner rig and segmented collector configuration illustrating the method of injecting the dopant into the combustor to insure complete vaporization. The cylinder is stationary with the segmented collector facing the exit nozzle of the burner.

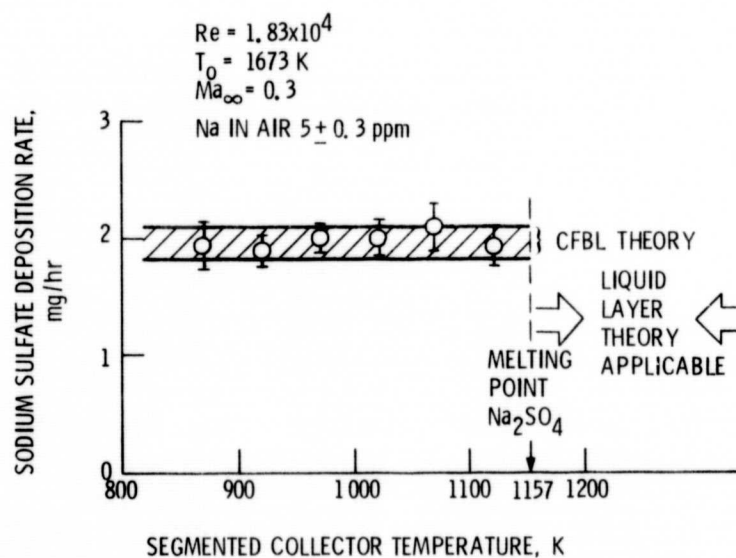


Figure 6. - Comparison of predicted and experimental sodium sulfate plateau deposition rates on segmented collectors.

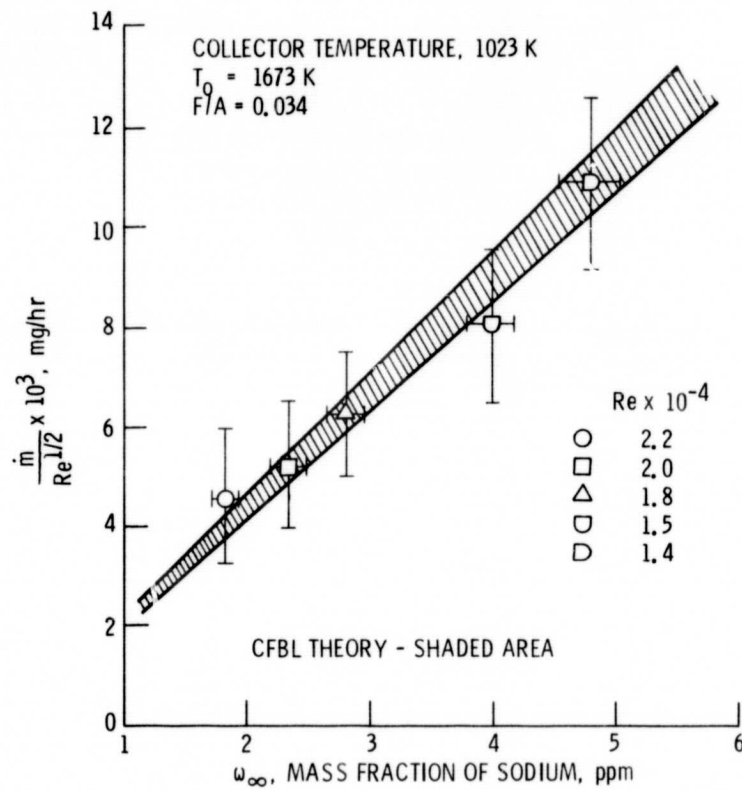


Figure 7. - Comparison of the predicted and experimental variation in deposition rates on segmented collectors with sodium concentration in the combustion gases and with the mass flow rate (Reynolds number).

1. Report No. NASA TM-87287		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Experimental Verification of Corrosive Vapor Deposition Rate Theory in High Velocity Burner Rigs				5. Report Date	
				6. Performing Organization Code 505-63-01	
7. Author(s) Süleyman A. Gökoğlu and Gilbert J. Santoro				8. Performing Organization Report No. E-2993	
				10. Work Unit No.	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546				14. Sponsoring Agency Code	
15. Supplementary Notes Prepared for 3rd Conference on High Temperature Alloys for Gas Turbines and Other Applications, sponsored by the Commission of the European Communities, Liège, Belgium, October 6-9, 1986. Süleyman A. Gökoğlu, Case Western Reserve University, Dept. of Mechanical Aerospace Engineering, Cleveland, Ohio 44106 and NASA Resident Research Associate; Gilbert J. Santoro, NASA Lewis Research Center.					
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17. Key Words (Suggested by Author(s)) Deposition; Mass and heat transfer; Boundary layer; Hot corrosion; Combustion			18. Distribution Statement Unclassified - unlimited SIAR Category 34		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of pages	
				22. Price*	